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Development and Research of Peristaltic Multiphase Piezoelectric Micro-pump

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ABSTRACT

The paper presents the results of a study of existing models and mathematical representations of a range of truly peristaltic multiphase micro-pumps with a piezoelectric actuator (piezo drive). Piezo drives with different types of substrates use vertical movements at deformation of individual piezoelectric elements, which define device performance. The dependences of the maximum micro-pump output pressure from the difference between the phases of voltage drives are established. The dynamic properties of piezo drive, deformation forms of its individual piezoelectric elements were defined by theoretical and experimental methods. The dependence of micro-pump output pressure from the phase frequency and difference was determined.

KEYWORDS
Peristaltic piezo micro-pumps, signaling, deformation of piezo drive, piezoelectric actuator, bending vibrations

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Introduction

Peristaltic piezoelectric micro-pumps are compact devices (in dimensions of centimeters) for pumping normal, viscous and mixing-sensitive liquids with a capacity from 1 ml/min to 100 ml/min (Nguyen & Wereley, 2006; Laser & Santiago, 2004; Kim et al., 2009). Such devices are widely used in medical, biological and chemical researches for solving problems of highly precise delivery of small liquid volumes (Au, Lee & Folch, 2014; Schilling et al., 2012; Jeong et al., 2015). The main operating element of studied piezo micro-pumps is a piezoelectric actuator in the form of a rectangular plate, consisting of an elastic foundation and the piezoelectric elements arranged in a row (Valdovinos et al., 2013; Vasuki, Sathiya & Suresh, 2013; Joo et al., 2015). Applying electric signal with a certain phase difference on contiguous piezo elements, progressive wave of bending deformations arises, moving the liquid in the elastic micro-pump passage, where a piezo drive is fixed (from pump inlet to the output).

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At the present time, quasi-peristaltic pumps are widespread, where the movement of fluid is happening gradually by moving the fluid from one chamber to another by the bending deformations of the drive membrane located at each section [4; 10; 11]. Sections are separated by elastic flaps; sometimes drive membrane plays the role of the flaps. The advantage of such configuration is the high manufacturability, and disadvantages are intermittent flow and the impossibility of pumping viscous fluids and fluids with solid particles due to obstruction of flaps (Nguyen & Wereley, 2006; Laser & Santiago, 2004; Jeong et al., 2015).

This paper presents the design and study of the micro-pump, where shortcomings associated with the division of the pump chamber into separate sections were eliminated. Developed model of a peristaltic piezoelectric micro-pump was studied, where progressive wave of deformations is being distributed along the single elastic passage, allowing to provide high flow continuity with volatility of less than 5%.

Aim of the Study

Considering the model of the peristaltic piezoelectric micro-pump.

Research questions

How to determine the dynamic characteristics of the piezoelectric micro-pump?

Method

Deformation forms of separate piezo elements with the help of a special testing facility, shown in Figure 3, were defined by experimental methods. Testing facility includes a laser displacement meter (1) with detecting head (2) (measuring accuracy ±0,5 μm); power-generating unit B5-50 (3) (continuous voltage up to 300V); positioning stage (4) with supporting bracket to attaching detecting head (2); digital USB microscope (5) connected to a personal computer (6) and model of piezo micro-pump with eight piezo elements (7). The continuous voltage applied to the analyzed piezoelectric element (№52) is 80 V.

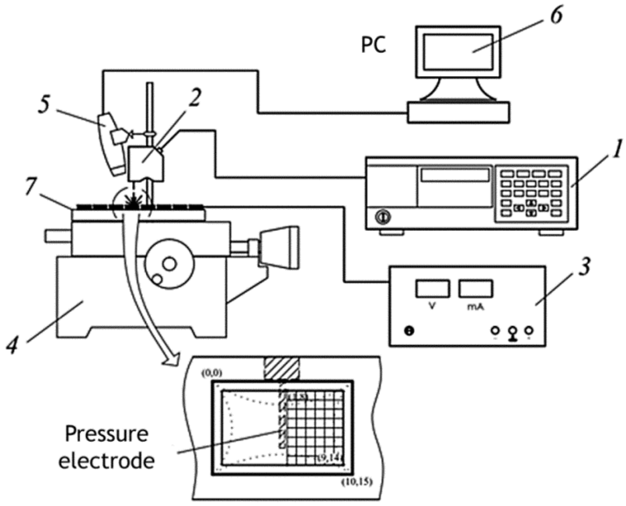
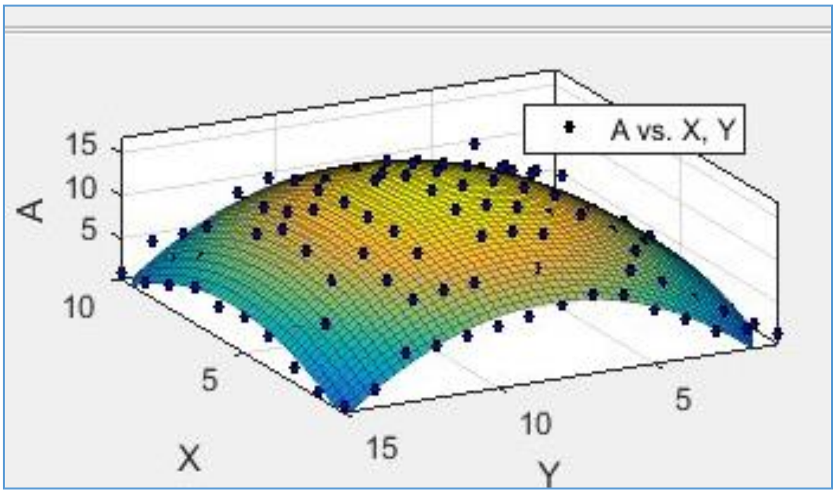


Figure 1. Graphic pattern of the experimental installation for determining the deformation of individual elements of piezo micro-pump

The chart of vertical movement of piezoelectric element №52, determined by experimental method, is shown in Figure 4, a), b). The maximum vertical movement in the center of the piezoelectric element is 16.0 μm.

1,5	1	1	1,5	1,5	2,5	2,5	1,5	1,5	1,5
2,5	3	4	3,5	6,5	6,5	5	4,5	4	2,4
3	5	5,5	8	7	8,5	7,5	7	6,5	3,5
5	7,5	9,5	10	10,5	13	12	10	7,5	6
6,5	9,5	10	12,5	13	14	13	11	9	6
9	9,5	10,5	13	14,5	15	16	11	10	7
9,5	10	13	14,5	16	16	14,5	13	9,5	7,5
9	11,5	14	15,5	16	16	15	13,5	10	7,5
8	10,5	14	15,5	16	16	14,5	13	8,5	6,5
7,5	11	12,5	12,5	14	16	12	12,5	10,5	7,5
7	10,5	13	14	14	14	13,5	13	11,5	7
6,5	10	10,5	12	11	13,5	11,5	10,5	10,5	4,5
6	6	7	9,5	11	12	9,5	7,5	7	4,5
2,5	3	6,5	6	6	7	5,5	5,5	3,5	4
1	1	2	4	4,5	4	4,5	3	1,5	1

a)



b)

Figure 2. Vertical movement of the piezoelectric element during deformation: a) - a horizontal chart of deformations; b) - a perspective view of a deformed shape with designation data points (black dots)

Data, Analysis, and Results

Figure 1 shows a developed micro-pump model consisting of a piezoelectric actuator (1) that is rigidly fixed with screws in the body (2) made of PMMA (polymethyl methacrylate), electrical connections for supplying piezo elements with the electrical signal (3), the input (4) and output (5) of silicone tubes. Dimensions of micro-pump body are 164x30x20 mm; dimensions of piezoelectric actuator are 114x20x0.23 mm. Piezo drive (Figure 2) consists of a substrate (1) on which piezoelectric elements (3) are mounted by a solder layer (2). The substrate material is stainless steel 12Cr18Ni10Ti (ρ = 7920 kg/m^3; E = 198 GPa; v = 0,3); the solder for attaching the piezoelectric elements on the substrate – (Silver soldering-50) Silver soldering-2 (ρ = 9400 kg/m^3; E = 16 GPa; v = 0,33). Piezo elements are made of piezoelectric ceramics PZT -19 (ρ = 7500 kg/m^3; d_{31}= –126 pC/N; d_{33}= 307 pC/N; d_{15}= 442 pC/N; e_{31}= – 4,9 C/m^2; e_{33}= 14,9 C/m^2;

e_{15}=10,6 C/m^2; $c_{11}=c_{22}$ = 109 GPa; $c_{12}=c_{21}$ = 61 GPa; $c_{31}=c_{32}=c_{13}=c_{23}$ = 54 GPa; $c_{44}=c_{55}=c_{66}$ = 24 GPa). Where ρ – density, E – elasticity modulus, ν – Poison's ratio.

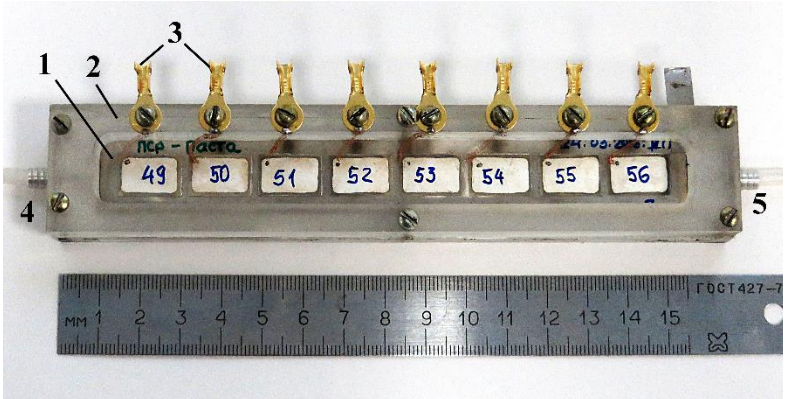


Figure 3. The current model of the peristaltic piezo micro-pump

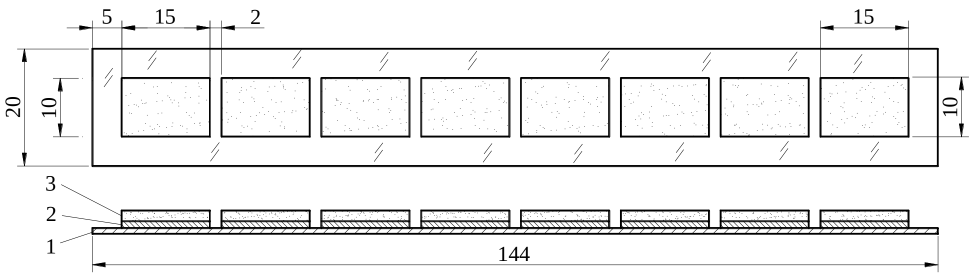


Figure 4. General scheme of piezoelectric actuator of peristaltic micro-pump
On the illustration: 1 – substrate, h = 0,05 mm; 2 – solder, h = 0,08 mm; 3 – piezo element, h = 0,1 mm. Where h – thickness of the layer.

Design of piezo drive was also studied by the finite element method in program APM Structure 3D 11.0 using a temperature analogy of piezoelectric effect. Charts of vertical movements and equivalent stresses of piezo actuator are presented in Figure 5 a), b). The chart of vertical movements shows peaks and troughs with maximum amplitude of about 16 μm, corresponding to the bending vibrations of the drive piezoelectric elements. Applying serial connection with some phase difference, traveling wave, which continuously transports the fluid from the pump inlet to the outlet, appears. At equivalent stresses chart we can see that stress areas exceeding the solder creep limit (20 mPa) are located near the edges of piezoelectric elements and they are local (about 0.5 mm in width) that does not lead to the formation of plastic hinge across the bond area. Thus, the durability of the structure is provided.

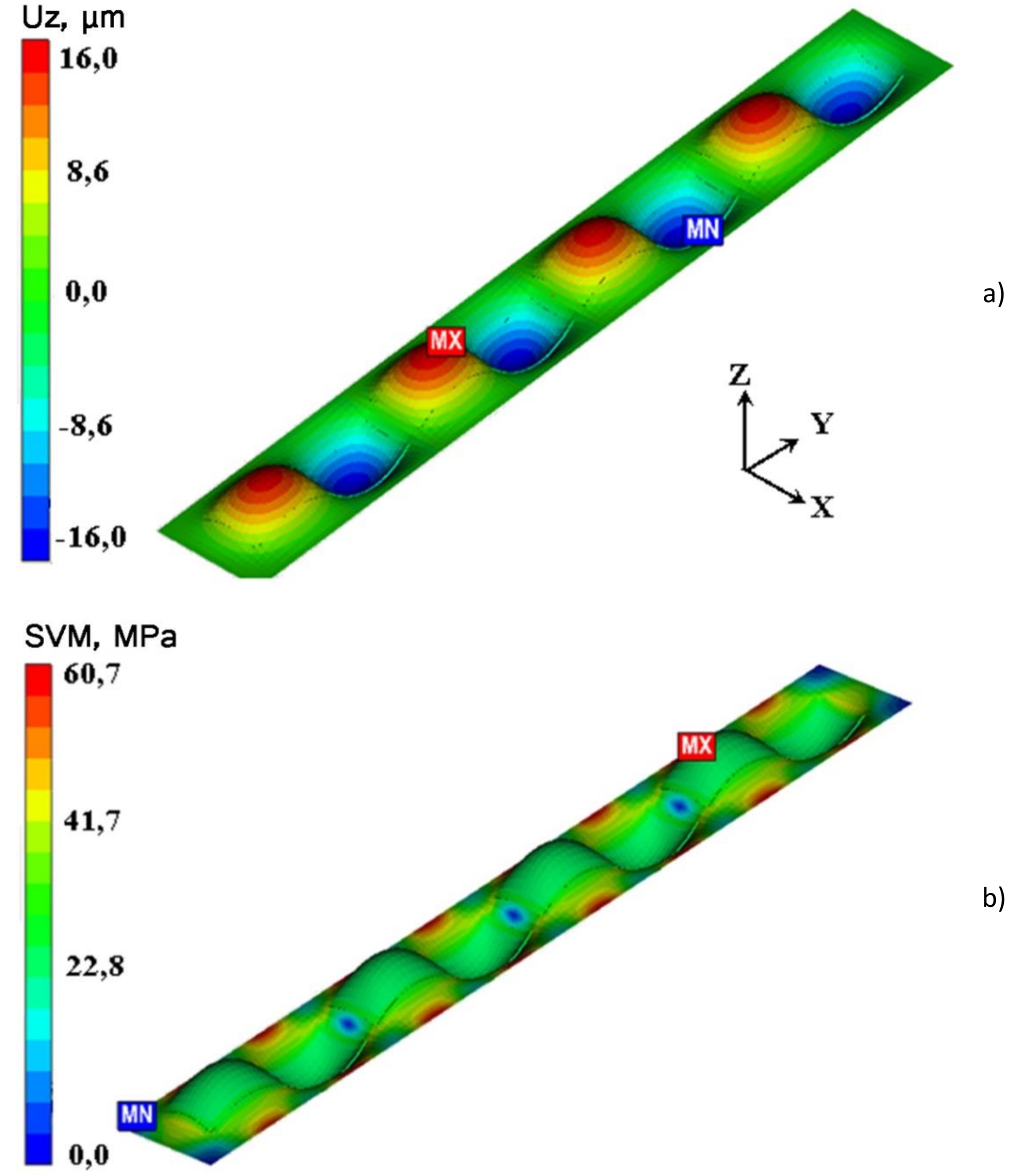


Figure 5. Results of the micro-pump study using finite element method (FEM) – a) chart of vertical movement UZ, µm, b) – chart of equivalent stresses SVM, mPa.

The process of studying using two methods showed similar profiles of deformed surface (Figure 6). The difference of the vertical movement values calculated in two ways does not exceed 10% in the central part of the piezoelectric element. The maximum movement in the center obtained by experimental method is 16.00 µm, and by the finite element method – 15.68 µm. Significant errors near the borders of piezo element (up to 60%) are caused by low absolute values of movement, comparable to the value of the instrument error ± 0,5 µm. Moreover, error at the edges may be caused by a difference in boundary conditions of fastening physical and theoretical model.

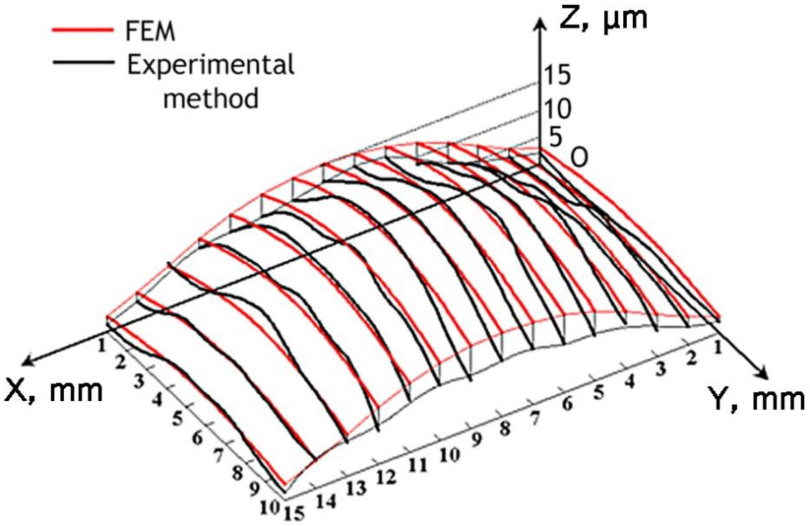


Figure 6. Deformed surface of the piezoelectric element obtained by experimental and numerical (FEM) methods

In order to determine the dynamic characteristics of piezo micro-pump, structural modal analysis was undertaken. The first 10 structural movements and the corresponding forms were identified. It was found that the frequency f = 2,335 kHz corresponds to the eighth form of bending vibrations (Figure 7), in which each individual piezoelectric element performs bending vibrations corresponding to the operating mode.

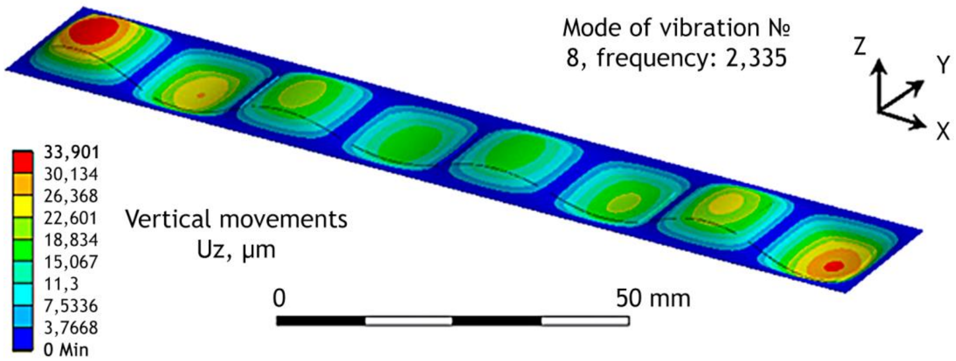


Figure 7. Eighth form, when f = 2,335 kHz corresponds bending vibrations of a single piezoelectric element

Discussion and Conclusion

The dependence of the value of an output pressure of a peristaltic micro-pump model (on aeneus substrate) on the frequency and phase difference signal, which is applied on adjacent piezoelectric elements, was estimated by experimental method. Experimental arrangement included the model of the micro-pump, the inlet tank with a liquid (water), outlet pipe for measuring the height of the column of fluid, high voltage signal generator, controlled by a personal computer.

During the experiment, we studied the dependence of height of the column of fluid dH (1 mm water column or 9.81 Pa) in the outlet tube from the phase difference $\Delta\varphi°$ of electrical signal applied to the adjacent piezoelectric elements with the interval $20° < \Delta\varphi < 75°$. Voltage amplitude was 100V, and the waveform was sinusoidal. It was found that with the increasing of phase difference $\Delta\varphi°$, linear increase of the height of liquid column occurs. It can be described by the expression $dH = 0{,}64\Delta\varphi° + 2{,}84$ (approximation accuracy $R2 = 0{,}936$) with a slight decline in $\Delta\varphi = 50 \ldots 60°$ (Figure 8). Increasing of the phase difference greater than 75° results in mechanical damage of piezoelectric elements.

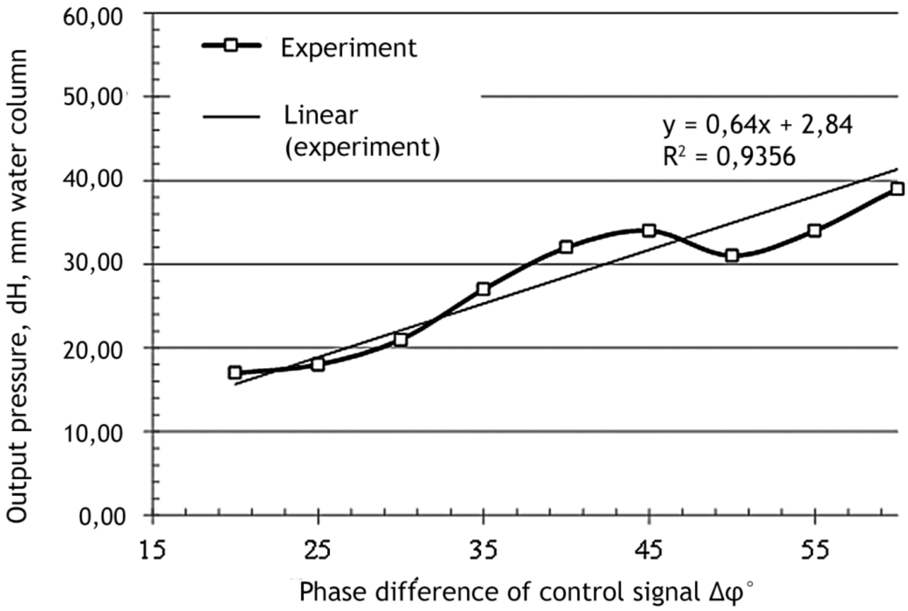


Figure 8. Dependence of the output pressure of the micro-pump dH, mm water column from phase difference of control signal $\Delta\varphi$

It is also found that the maximum pressure with an increase in phase difference is being shifted to higher frequencies (if $\Delta\varphi = 20°$ height $dH_{max} = 17$ mm (167 Pa) at f = 5 Hz, when $\Delta\varphi = 75°$ $dH_{max} = 57$ mm (657 Pa) even at f = 36 Hz) (Figure 9).

Furthermore, low-frequency region ($30° < \Delta\varphi < 45°$) is characterized by two output pressure peaks. Probably, this is due to the fact that one mechanism of expelling liquid, which is manifested at small shifts of the phases and inherent to low frequency, is replaced by another, typical for this system, working at high phase shifts and taking place at higher frequencies.

According to the literature, the maximum capacity of peristaltic piezo micro-pumps is observed at frequencies from 30 Hz to 60 Hz, which adjusts with the results of the research. For example, in the article (Kim et al., 2009) the maximum back pressure of 640 Pa is reached at a frequency of 50 Hz and a voltage of 200 V, in (Oh et al., 2009) – the maximum back pressure of 850 Pa is achieved at a frequency of 57 Hz and a voltage of 150 V.

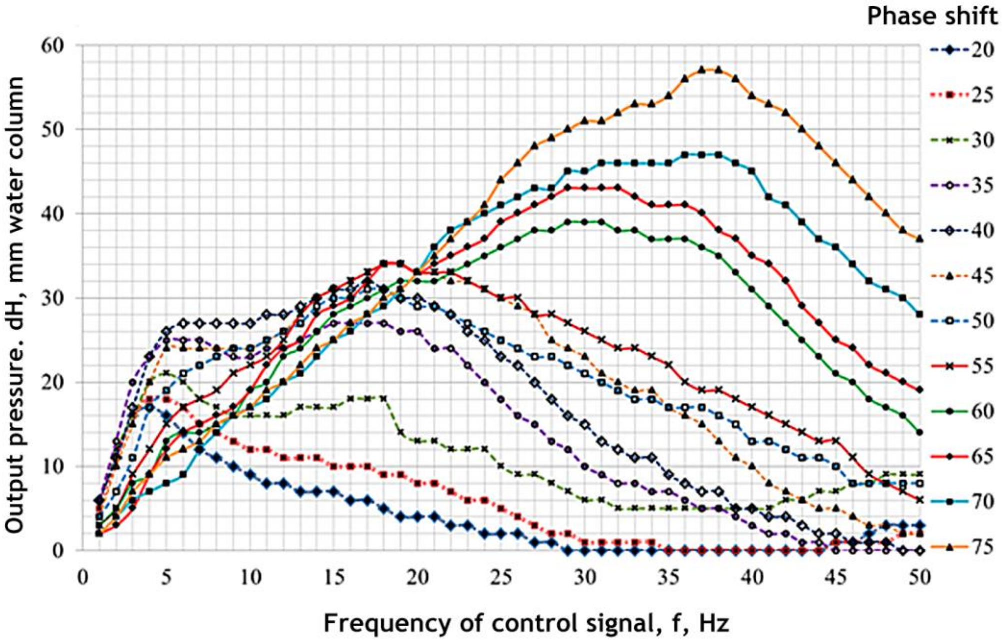


Figure 9. Dependence of the output pressure dH from the frequency f at certain values of the phase difference Δφ

Implications and Recommendations

1. Vertical movement at the bending deformation of the piezo drive on a steel substrate was defined by theoretical and experimental methods. The maximum movement of the center of the piezoelectric element is 15.68 µm, according to theoretical calculations (finite element method), and 16,0 ± 0,5 µm, according to the full-scale experiment. The difference in results does not exceed 2%. Comparing the profiles of deformed surfaces, we found that vertical movement in the peripheral zone of the piezoelectric element, calculated by an analytical method, substantially (by tens of percent) exceeds the movement, which were measured experimentally. This fact demonstrates the need to clarify the theoretical (FEM) calculation method by specifying boundary conditions of the problem.

2. The dependence of outlet pressure of the model of the peristaltic micro-pump from the frequency and the phase difference of control signal frequency between adjacent piezo elements was studied. It is found that the magnitude of the back pressure increases linearly with the phase difference by the formula $dH = 0{,}64\Delta\varphi + 2{,}84$ (up to 567 Pa at $\Delta\varphi = 75°$). Maximum back pressure is shifted to higher frequencies with an increase in the phase difference. At low-frequency region, when $30° < \Delta\varphi < 40°$ two peaks are observed on the frequency of back-pressure, associated with a different fluid expelling mechanisms at lower and higher frequencies. The experimental results adjust with literature data.

Disclosure statement

No potential conflict of interest was reported by the authors.

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